technische universität
dortmund

Theoretische Physik III /
Fakultät Physik

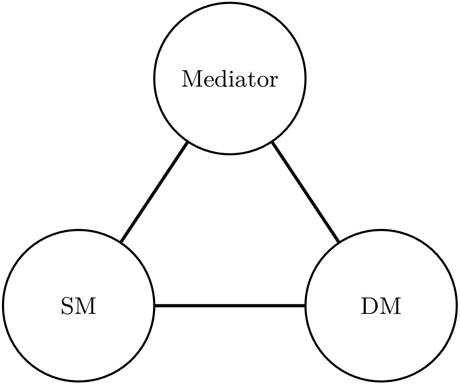
Dark Matter with Yukawa Interactions - feeble or not?

Mathias Becker

Overview

- Dark Matter Production
- Experimental Constraints
- Portals to Dark Matter: Neutrino Portal
- Portals to Dark Matter: The Higgs Portal

Dark Matter Production [Hambye et. al (2019)]



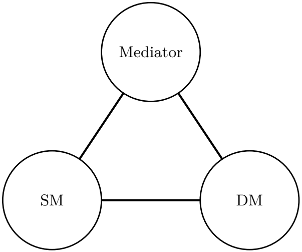
Boltzmann Equations

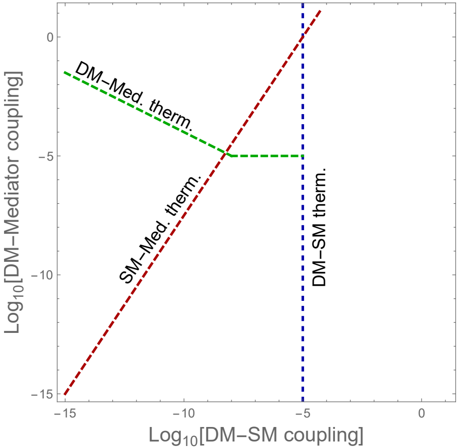
Boltzmann-Equations

$$\frac{dY}{dt} \sim -\frac{\Gamma}{H}\left(\prod_{i\in I}\frac{Y_i}{Y_i^{eq}} - \prod_{f\in F}\frac{Y_f}{Y_f^{eq}}\right)$$

- Process Efficiency? $\rightarrow$ Compare Γ to $H \sim T^2 M_{Pl}^{-1}$
  $\rightarrow$ If $\Gamma \ll H$ process decouples; If $\Gamma \gg H$ process is in equilibrium

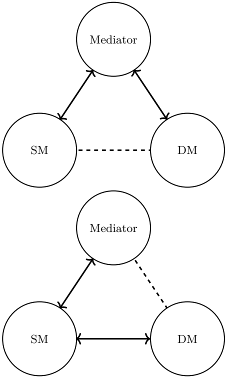
Dark Matter Production [Chu,Hambye,Tytgat (2011)]



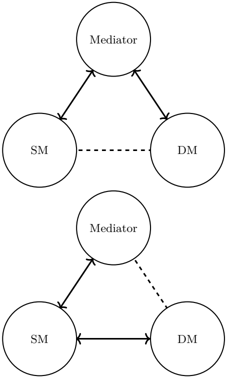


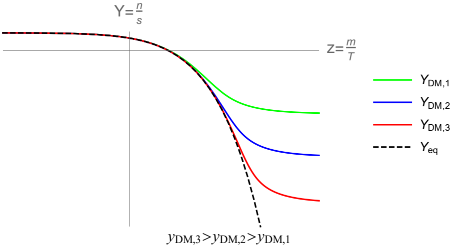
Do not forget: We assume (SM-DM) = (SM-Mediator) · (Mediator-DM)

Dark Matter Production – Freeze-Out



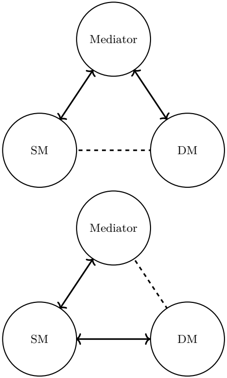
Dark Matter Production – Freeze-Out

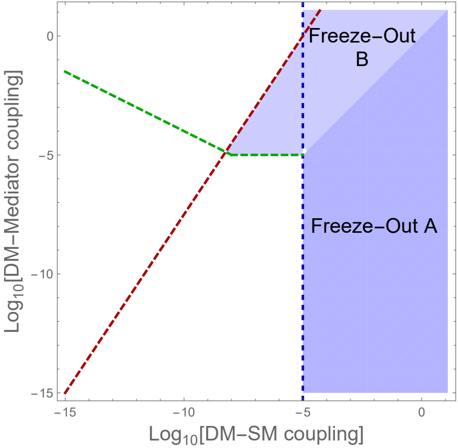




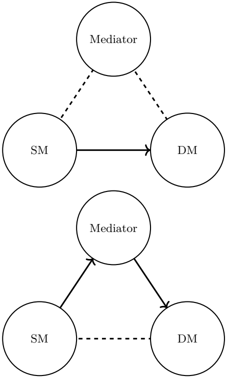
- DM density decreases with an increasing coupling
- $\Omega_{\mathrm{DM}} \sim <\sigma v>^{-1} M_{\mathrm{DM}}$
- Typically bounds DM mass from above

Dark Matter Production – Freeze-Out

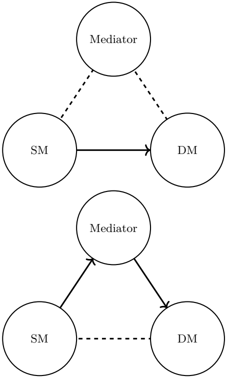


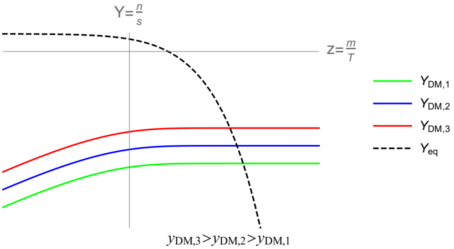


Dark Matter Production – Freeze-In [Hall et. al(2009)]



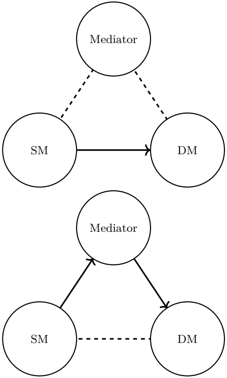
Dark Matter Production – Freeze-In [Hall et. al(2009)]

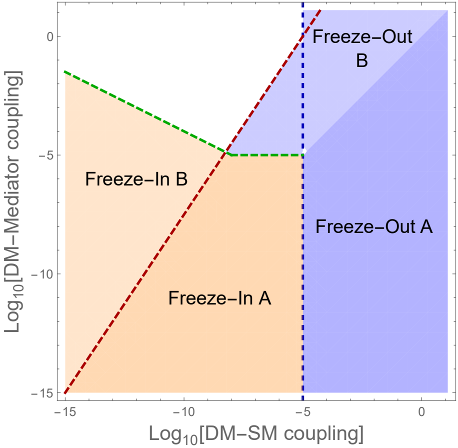




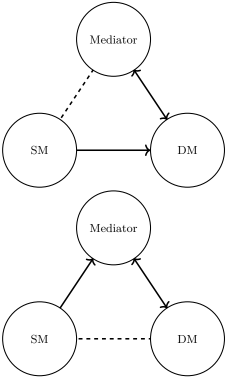
- DM density increases with an increasing coupling
- $\Omega_{DM} \sim M_{max}^{-1} M_{DM}$

Dark Matter Production – Freeze-In

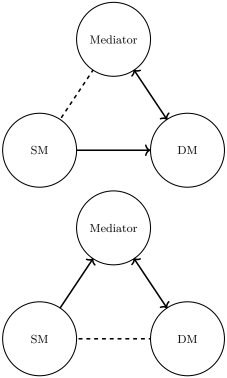


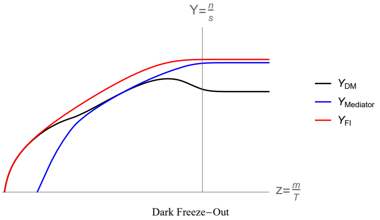


Dark Matter Production – Dark Freeze-Out



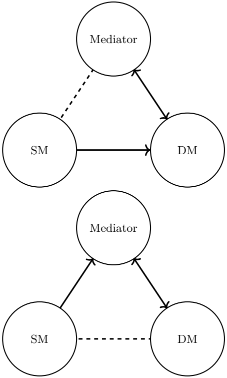
Dark Matter Production – Dark Freeze-Out



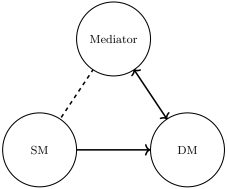


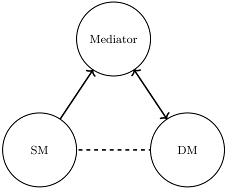
- Energy transfer into the dark sector (DS) stops before the DS self-interactions decouple.
- A larger SM-DS coupling increases Ω_{DM}
- A larger DS self-interaction decreases Ω_{DM}.

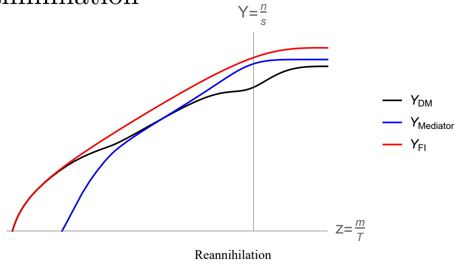
Dark Matter Production – Reannihilation



Dark Matter Production – Reannihilation







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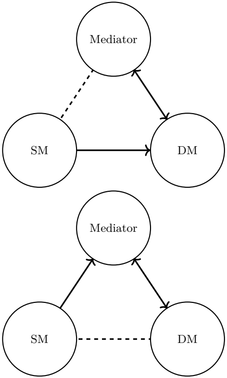
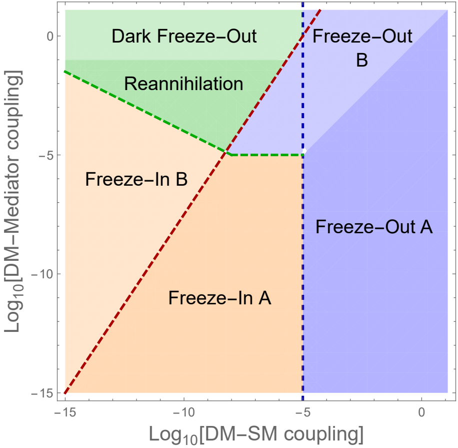
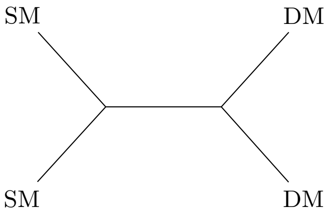
- A larger DS self-interaction

Dark Matter Production – Reannihilation

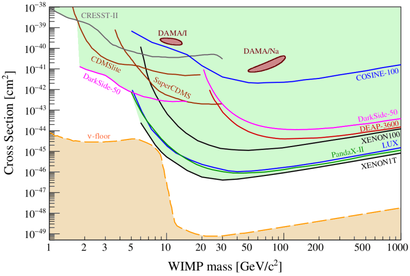




Experimental Constraints



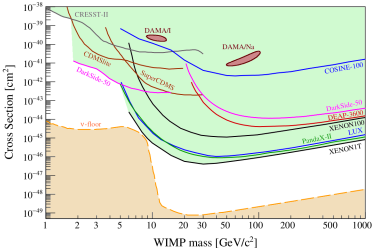
Direct Detection



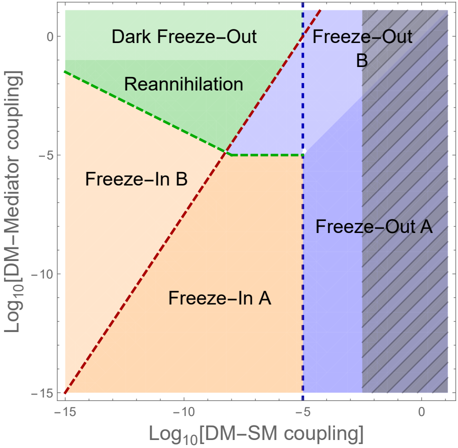
[1903.03026]

- Search for DM scattering with nucleons on earth.
- Looses sensitivity for $M_{DM} \lesssim 10\,\text{GeV}$.
- Constrains the DM-SM coupling.
- Light Mediators: Even Freeze-In can be tested [Hambye et. al (2018)]

Direct Detection



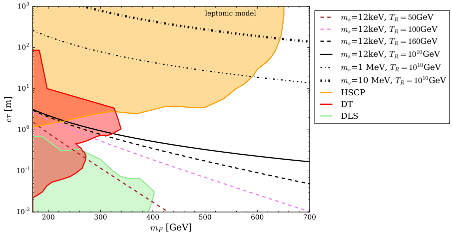
[1903.03026]

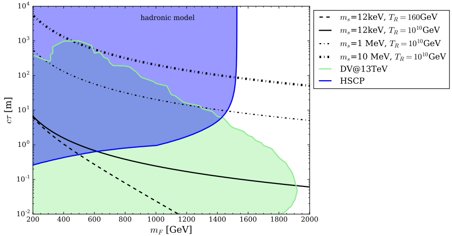


Collider Constraints

- Requires a sizeable SM-DM or SM-Mediator coupling.
- Large SM-DM : DM production and its signatures, e.g. missing energy.
- Large SM-Mediator can test feeble SM-DM interaction via long-lived particle searches.

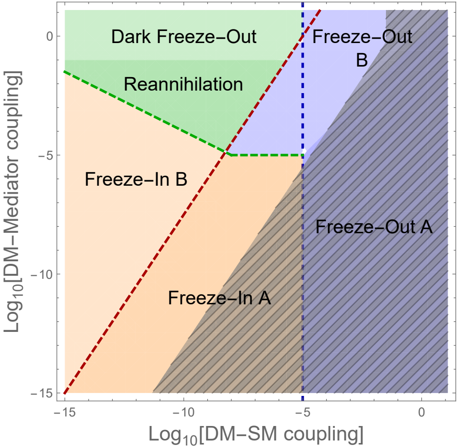
LHC friendly Freeze-In [Belanger et al (2018)]





- Lines indicate correct relic density
- Hadronic model: $m_F \geq 1.5\,\text{TeV}$
- A measurement of the leptonic model might rule out certain leptogenesis scenarios

Collider Constraints



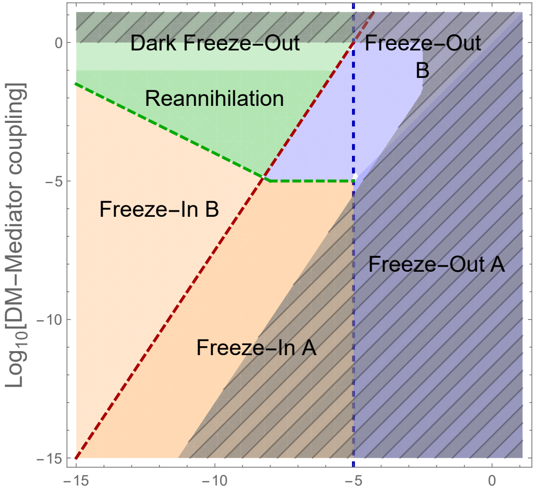
Astrophysical Constraints

- Tremaine-Gunn bound: Phase space-density in small halos leads to $M_{DM} \gtrsim 5\,\mathrm{keV}$ for fermions.
- BBN constraints particles that interact strongly with $e^{\pm}$, γ or ν: $M_{DM} \gtrsim 10\,\mathrm{MeV}$ (very model dependent).
- DM self-interaction is constrained to $\frac{\sigma_{DM}}{M_{DM}} \lesssim 1\,\frac{\mathrm{cm}^2}{\mathrm{g}}$ from Bullet Cluster.
- Lyman-α measurement typically requires $M_{DM} \gtrsim 5\,\mathrm{keV}$ for thermal DM.

Indirect Detection

- Typically less powerful than direct detection.
- Concept: DM annihilates into SM particles which can be observed on earth, e.g. γ-rays.
- For feebly interacting DM: DM decay products might be observed.

Together


Dark Freeze−Out
Freeze−Out
B
Reannihilation
Freeze−In B
Freeze−Out A
Freeze−In A
Log10[DM−Mediator coupling]
0
−5
−10
−15
−15
−10
−5
0

Portals to Dark Matter

Higgs Portal	Vector Portal	Neutrino Portal
$\left(\phi^\dagger \phi\right) \eta^2$	$B^{\mu\nu} B'_{\mu\nu}$	$\bar{L} \phi \nu_R$
[Arcadi,Djouadi,Raidal (2019)]	[Hambye et. al (2019)]	

Portals to Dark Matter

Higgs Portal	Vector Portal	Neutrino Portal
$\left(\phi^\dagger\phi\right)\eta^2$	$\mathrm{B}^{\mu\nu}\mathrm{B}'_{\mu\nu}$	$\bar{\mathrm{L}}\phi\nu_{\mathrm{R}}$
[Arcadi,Djouadi,Raidal (2019)]	[Hambye et. al (2019)]	

- N itself can be a DM candidate

  $\rightarrow$ simplest scenario tightly constrained from Lyman-α and $\mathrm{N} \rightarrow \nu\gamma$

The Neutrino Portal to Dark Matter

- Dark sector: Fermion χ and scalar η, stabilized by $\mathrm{U}(1)$ or $\mathcal{Z}_2$.

Lagrangian

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{kin,DS}} - \mathrm{V}_{\mathrm{sc.}} - \left(\bar{\nu}_{\mathrm{R}}\left[\left(\mathrm{y}_{\nu}\phi \mathrm{L} + \mathrm{y}_{\chi}\eta\chi_{\mathrm{L}}\right] + \mathrm{h.c.}\right)$$

The Neutrino Portal to Dark Matter

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Lagrangian

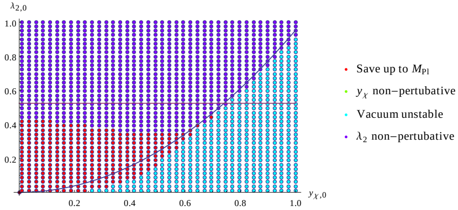
$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\mathrm{kin,DS}} - \mathrm{V}_{\mathrm{sc.}} - \left(\bar{\nu}_{\mathrm{R}} \left[\left(\mathrm{y}_{\nu}\phi \mathrm{L} + \mathrm{y}_{\chi}\eta\chi_{\mathrm{L}}\right] + \mathrm{h.c.}\right)$$

Type-I seesaw Freeze-Out	Inverse seesaw Freeze-Out	Type-I seesaw Freeze-In
[Escudero,Rius,Sanz (2016)]	[Batell et. al (2017)]	[MB (2018)]
[Escudero,Rius,Sanz (2016)]	[Batell,Han,Es Haghi (2017)]	[Chianese,King (2018)]
	[González Macías et. al (2016)]	

Vacuum Stability I

Scalar Potential

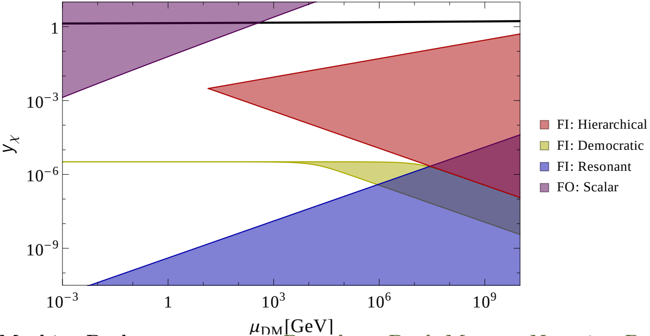
$$\mathcal{L} \supset -\mathrm{m}_\eta^2\eta^2 - \lambda_2\eta^4 - \lambda_{\phi,\eta}\left(\phi^\dagger\phi\right)\eta^2 - \mathrm{y}_\chi\bar{\chi}\nu_\mathrm{R}\eta$$



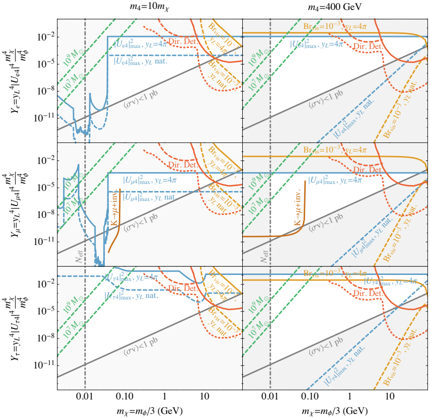
Vacuum Stability II

Analytic Estimate

$$\ln\left(\frac{\mu_{\lambda_2}}{\mu_{\mathrm{DM}}}\right) = \frac{4\pi^2\lambda_2\left(\mu_{\mathrm{DM}}\right)}{3y_\chi^4}$$



Neutrino Portal: Inverse Seesaw



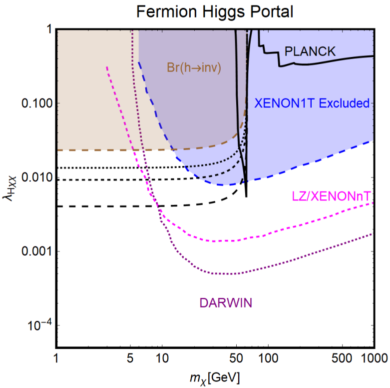
Fermionic Higgs Portal

Lagrangian

$$\mathcal{L} \supset \frac{1}{2}\mathrm{m}_\chi \bar{\chi}\chi + \frac{\lambda_{\mathrm{H}\chi\chi}}{\Lambda}\phi^\dagger\phi\bar{\chi}\chi$$

- Requires UV-completion.
- Mainly constrained by direct detection and Higgs invisible decay width.

Fermionic Higgs Portal



- Freeze-In scenarios still viable but UV-complete discussion necessary.
- Typically a 'Freeze-In A' scenario.
- Important: UV-complete discussion of freeze-out scenario can open up the parameter space again

Conclusions

- bla